Phobos grooves:

the inherited signature of an ancient parent body?

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Phobos in a nutshell

|	
Dimensions	26.8 × 22.4 × 18.4 km
Mean Radius	11.1 km
Mass	1.072×10^{16} kg
Volume	5 783.61 km^3
Bulk Density	1.876 g/cm^3
Semi-major axis	9376 km (Mars center)
Orbit	≈ 6000 km (Mars surface)
Roche limit P-M	10500 km
Inclination (Mars eq)	1.09 deg
Inclination (Ecliptic)	26.0 deg
Surface gravity	581.4 μg
Escape velocity	11.4 m/s = 41 km/h
Orbital period	7h 39.2 min

Phobos debated origin

Phobos formation from a disk of debris (Peale 2007):

i)   as a remnant of the formation of Mars (Safronov et al., 1986)

ii)   as the result of a collision between Mars and a large body (Craddock 1994, 2011; Singer 2007).

Spectra taken in more than 43 years of observations (Duxbury et al., 2013), show physical characteristics similar to low-albedo asteroids such as C-type (Masursky et al., 1972, Pang et al., 1980) or D-type (Murchie 1999, Rivkin et al., 2002, Lynch et al., 2007, Pajola et al., 2012) => asteroidal capture
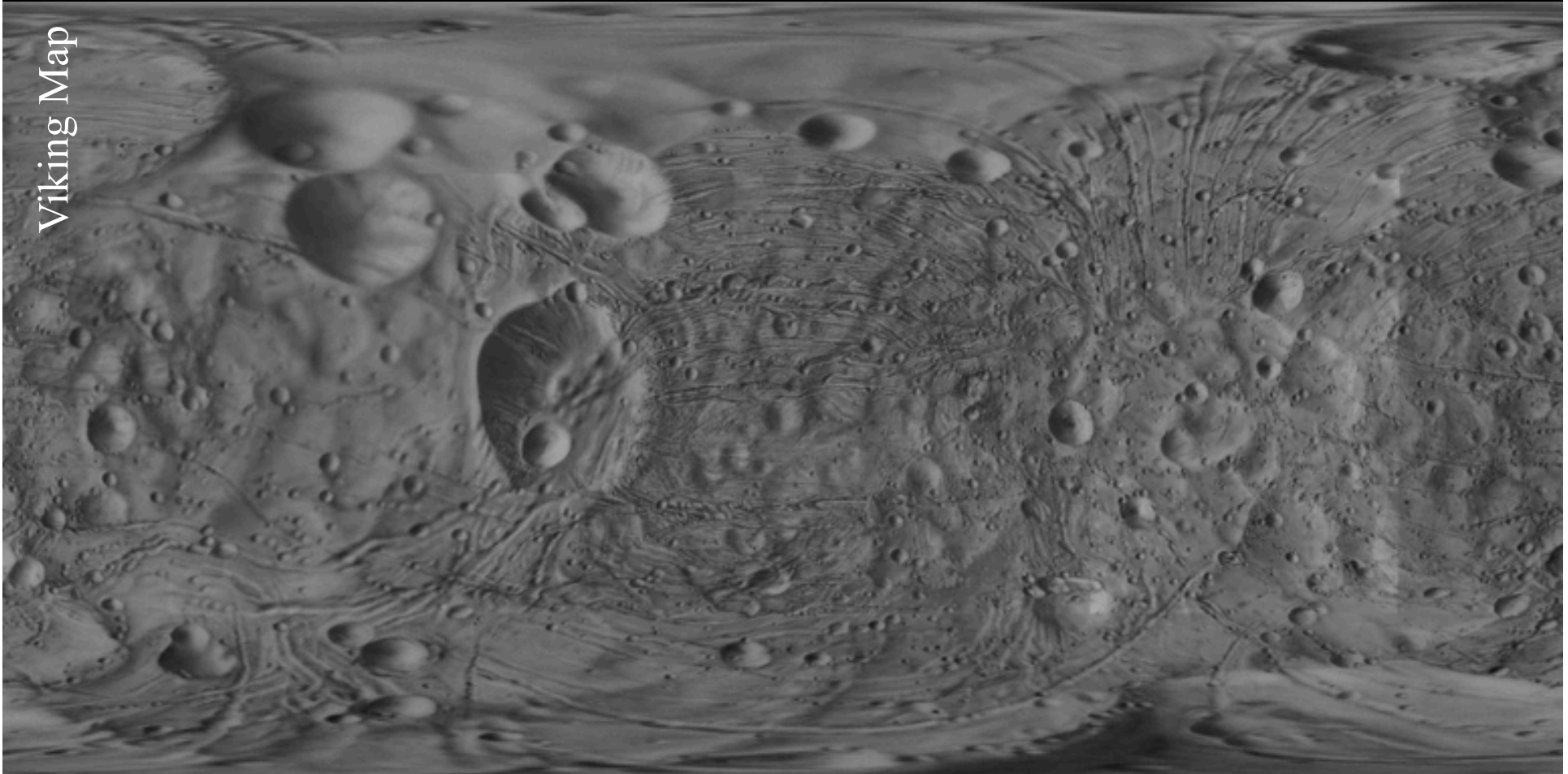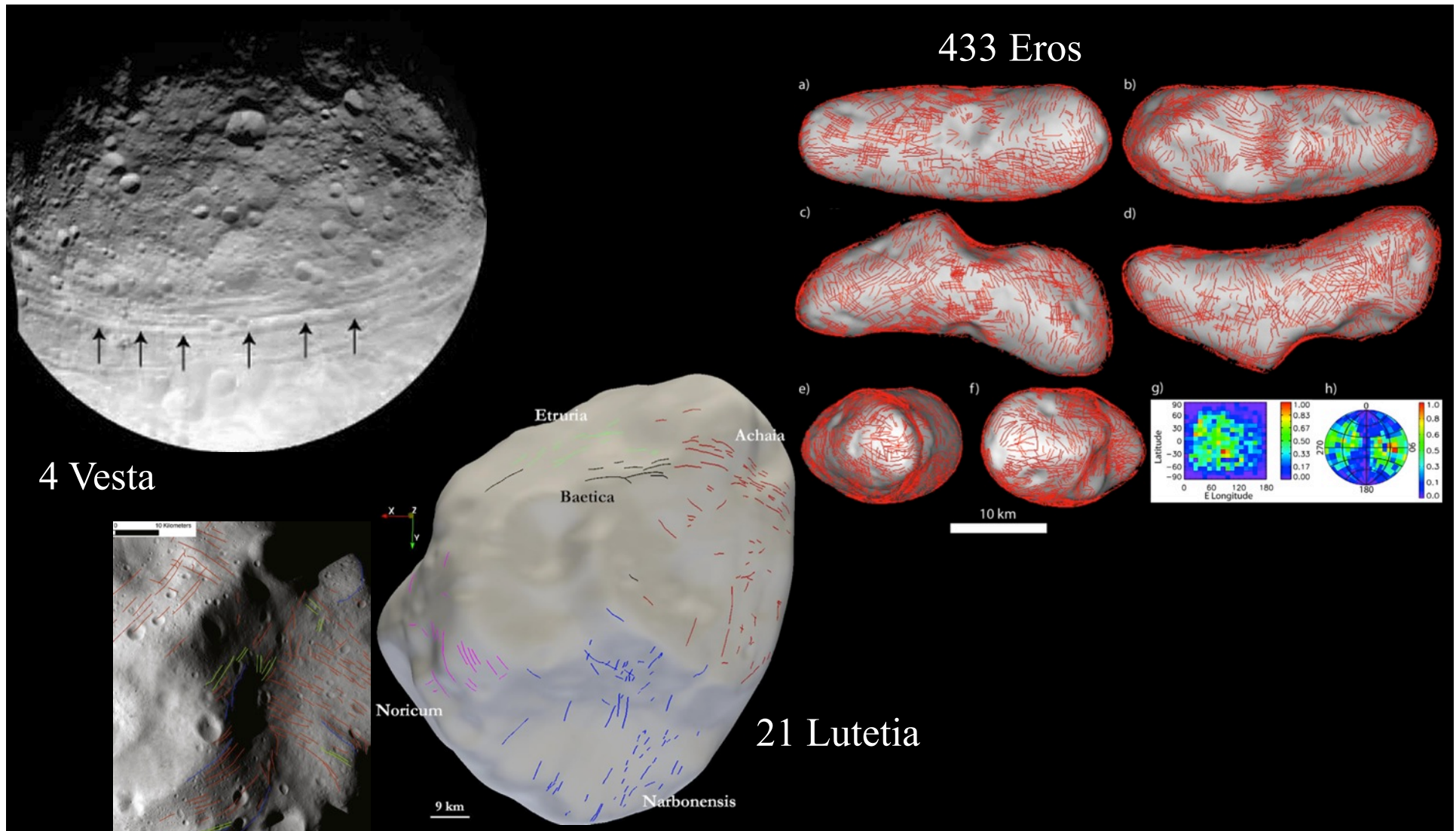
Phobos grooves

Phobos grooves

433 Eros

4 Vesta

21 Lutetia
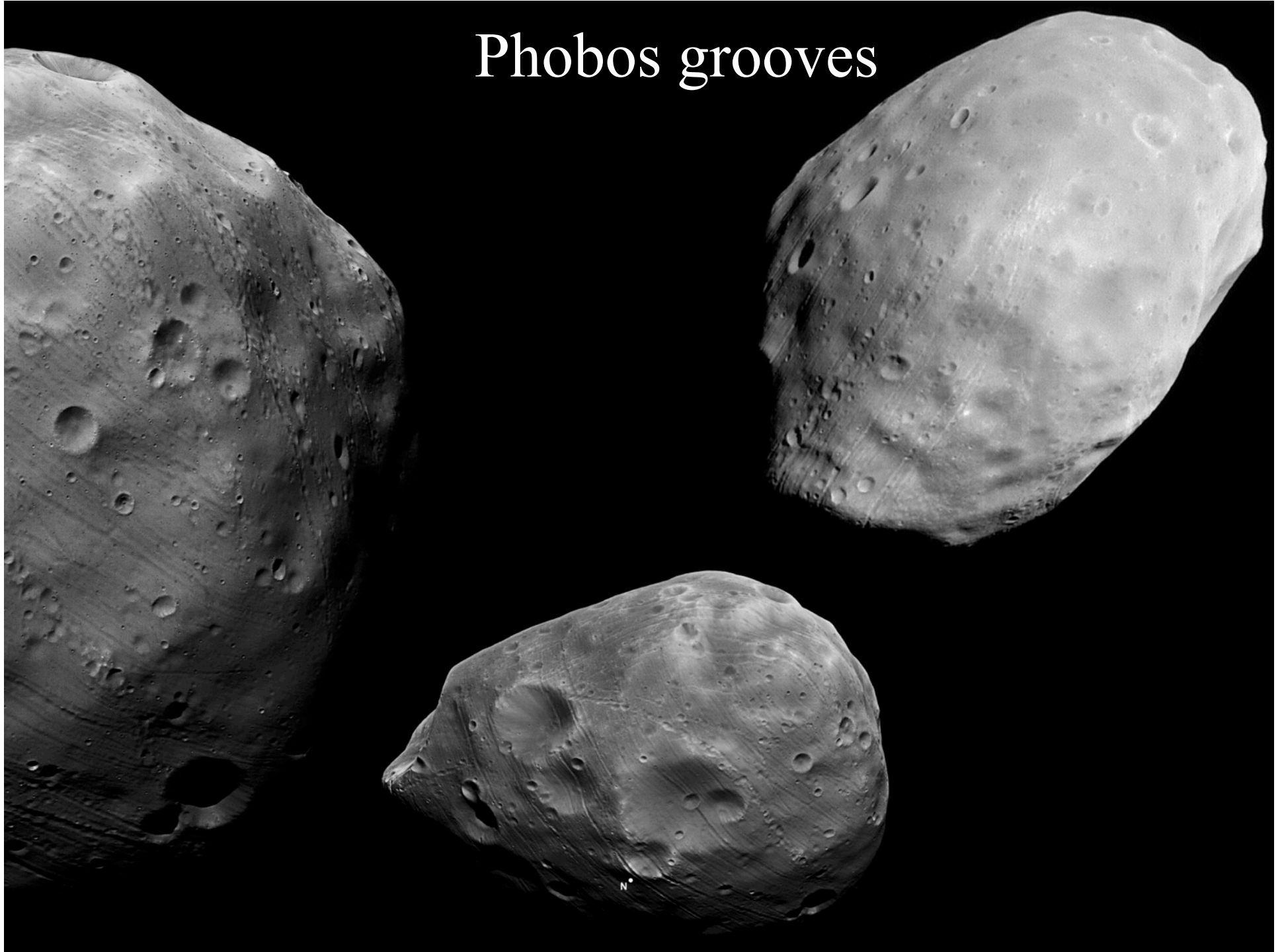
Grooves are a common feature on asteroids (Buczkowski and Wyrick, 2014), as presented from high-resolution images derived from multiple spacecrafts observing 951 Gaspra (Veverka et al., 1994), 243 Ida (Belton et al., 1994), 433 Eros (Thomas et al., 2002; Prockter et al., 2002; Buczkowski et al., 2008), 21 Lutetia (Massironi et al., 2012; Besse et al., 2014), 4 Vesta (Buczkowski et al., 2012).
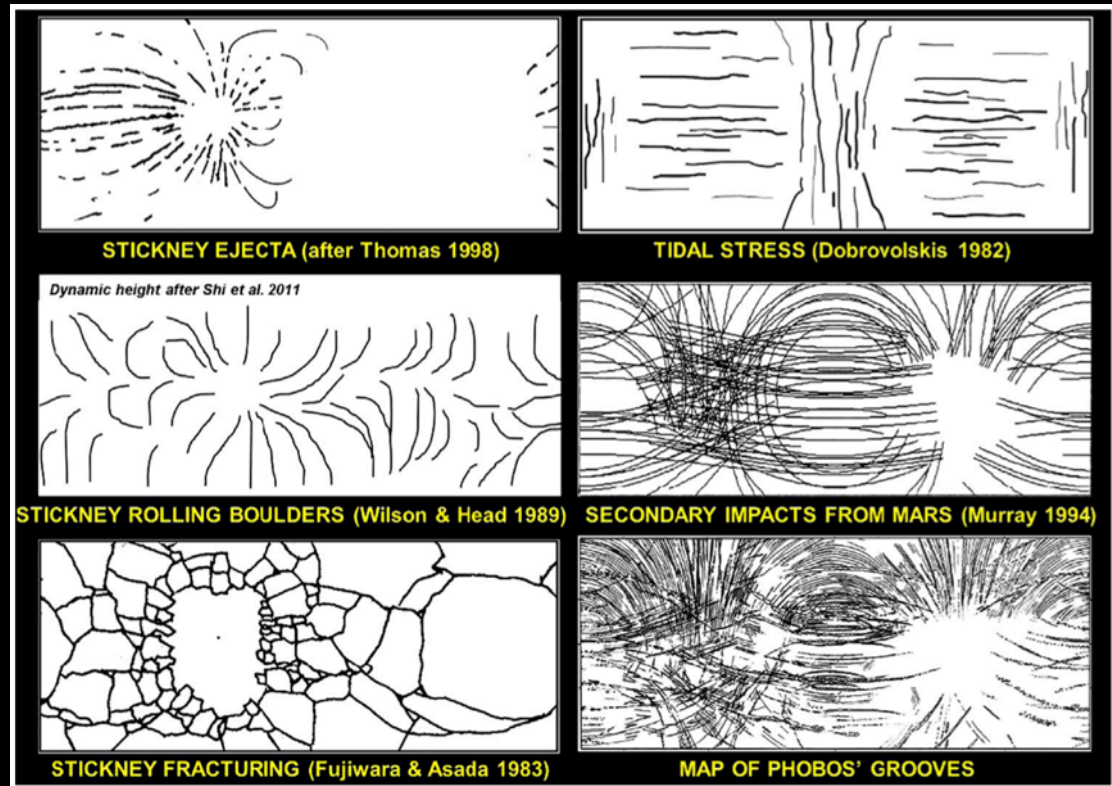
Phobos debated grooves

Phobos grooves were first observed in Viking images 38 years ago (Veverka and Duxbury, 1977). Since then, their origin have been greatly debated taking into consideration different evidences such as the Phobos actual orbit around Mars, well inside the Roche limit, and the presence of a 9 km wide crater on its surface, Stickney (Hamelin, 2011).

The origins of the Phobos grooves have been alternatively referred to:

(i) Mars tidal stress (Dobrovolskis, 1982);
(ii) dynamic loading due to the impact originating the 9 km Stickney crater (Fujiwara and Asada, 1983);
(iii) secondary impacts related to the Stickney crater (Wilson et al., 1989);
(iv) secondary impacts resulting from primary impact events on Mars (Murray et al., 1994; Murray and Iliffe, 2011; Murray and Heggie, 2014).

In Murray and Heggie (2014), a valuable summary of maps showing Phobos grooves orientation and distribution, as the results of the different possible origins, is presented.

From such work it is possible to determinate that Mars tidal stress alone would not result in the groove distribution observed on the surface. In addition the un-coeval origin of the grooves (Murray and Heggie (2014) and the evidence that several systems are younger than Stickney crater (Schmedemann et al., 2014; Murray and Iliffe, 2011; Murray and Heggie, 2014) would rule out the (ii) and (iii) scenarios.

STICKNEY EJECTA (after Thomas 1998)

TIDAL STRESS (Dobrovolskis 1982)

Dynamic height after Shi et al. 2011

STICKNEY ROLLING BOULDERS (Wilson & Head 1989)

SECONDARY IMPACTS FROM MARS (Murray 1994)

STICKNEY FRACTURING (Fujiwara & Asada 1983)

MAP OF PHOBOS' GROOVES

Finally according to a recent work (Ramsley et al., 2014) the volume of ejecta coming from Mars to Phobos appears to be insufficient to produce grooves of secondary craters.

Although Stickney impact fracturing seems to be inconsistent with the grooves distribution on Phobos (Murray and Heggie, 2014), the possibility that grooves are representative of fractures and joint planes still holds.

In this work we assume that grooves can be expressions of fracture planes, and we derive their spatial distribution and orientation on 3D reconstructions.
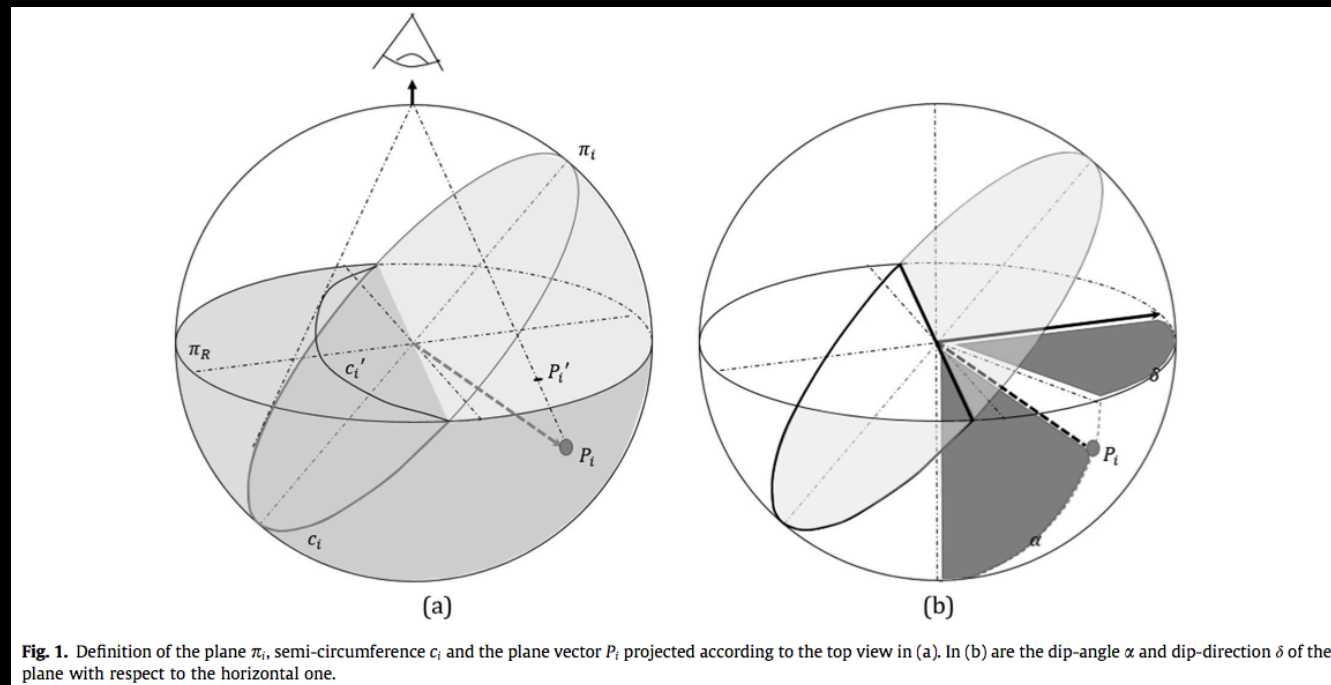

(d)
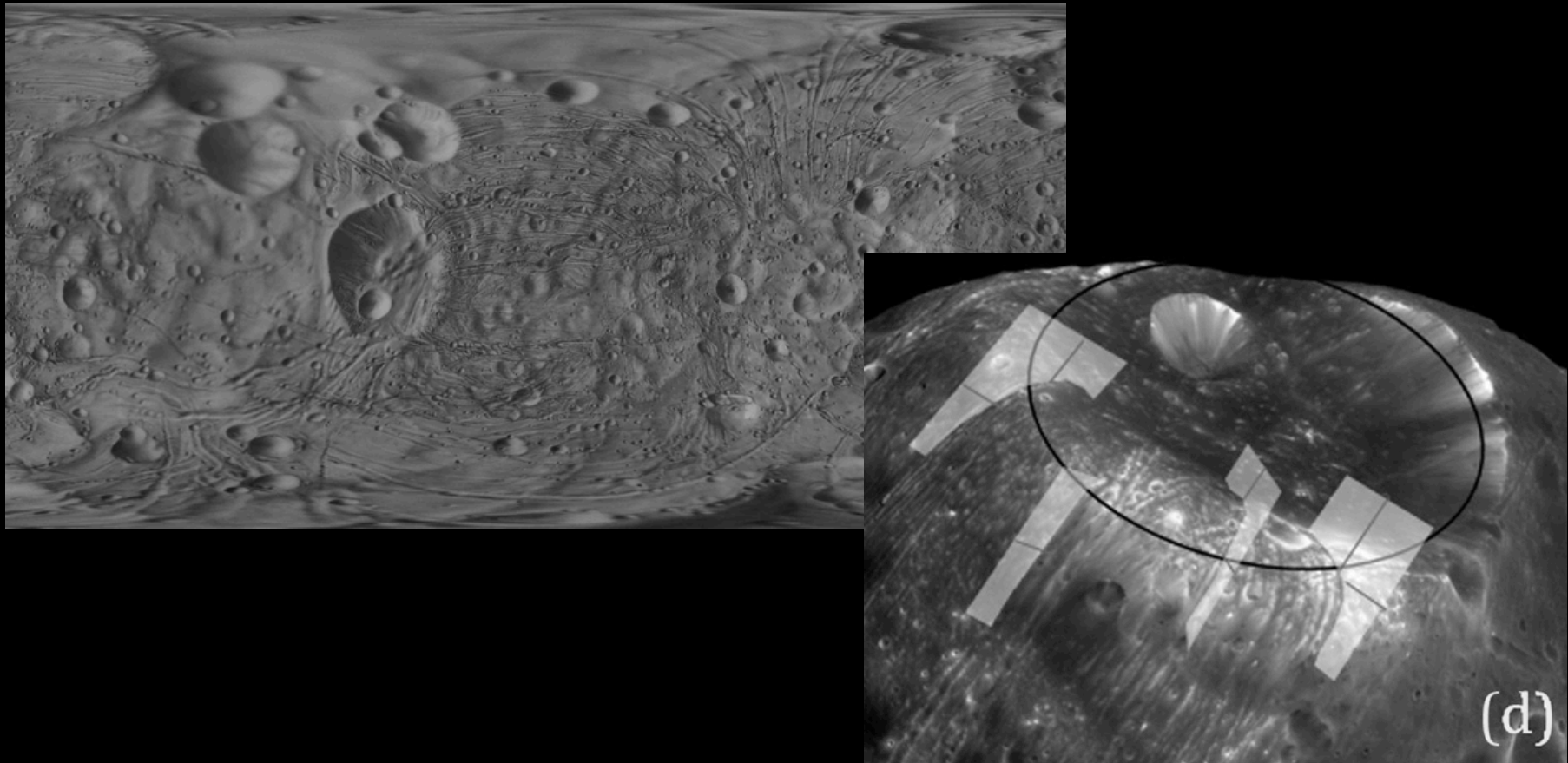
Stereo-plots and cyclographs represent two methods, unified under the name of stereographic projections, commonly used to describe the statistic of the orientations (dip-angle and dip-direction) of different planes with respect to a spherical or a plane surface (Bucher, 1944; Phillips, 1954; Ragan, 1985).

In order to consider only the orientations of a set of planes π_i with respect to a common reference plane π_R and not their relative spatial distribution, all planes must share the same centre of a reference sphere. A versor P_i univocally defines each plane p_i. Another way to represent the same plane is to consider the curve c_i that is the semi-circumference intersecting the reference lower hemisphere.

The projection of P_i and c_i on the reference plane π_R are respectively P'_i and c'_i.

The set of P'_i represents the stereo-plot, while the set of the c'_i is called cyclographic projection.

Fig. 1. Definition of the plane π_i, semi-circumference c_i and the plane vector P_i projected according to the top view in (a). In (b) are the dip-angle α and dip-direction δ of the plane with respect to the horizontal one.

The point P_i (and hence its projection P'_i) can be represented using two angles: the inclination or dip-angle a of p_i with respect to π_R, and the dip-direction δ of p_i with respect to the reference system of π_R. A given principal axis of plane π_R dotted in figure, is defined as the starting point to relate the clockwise angle of the dip-direction.
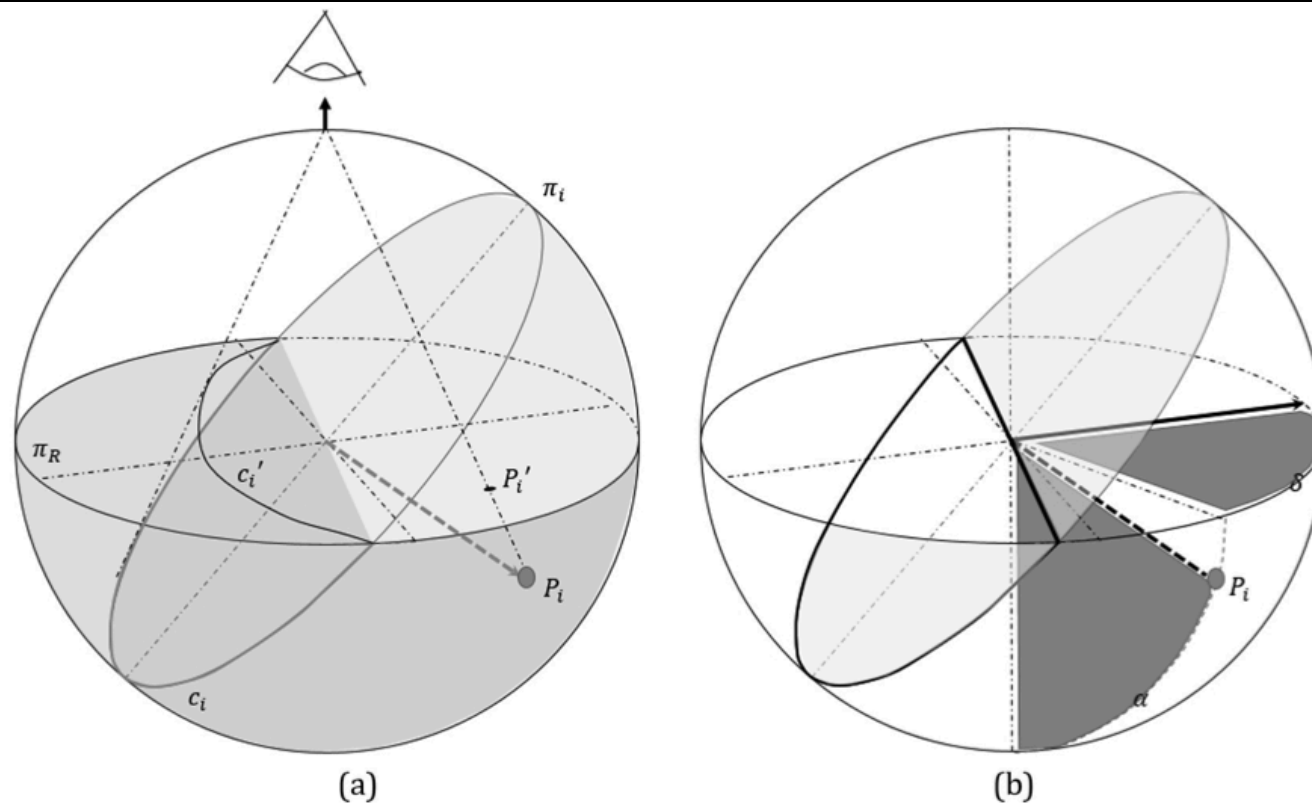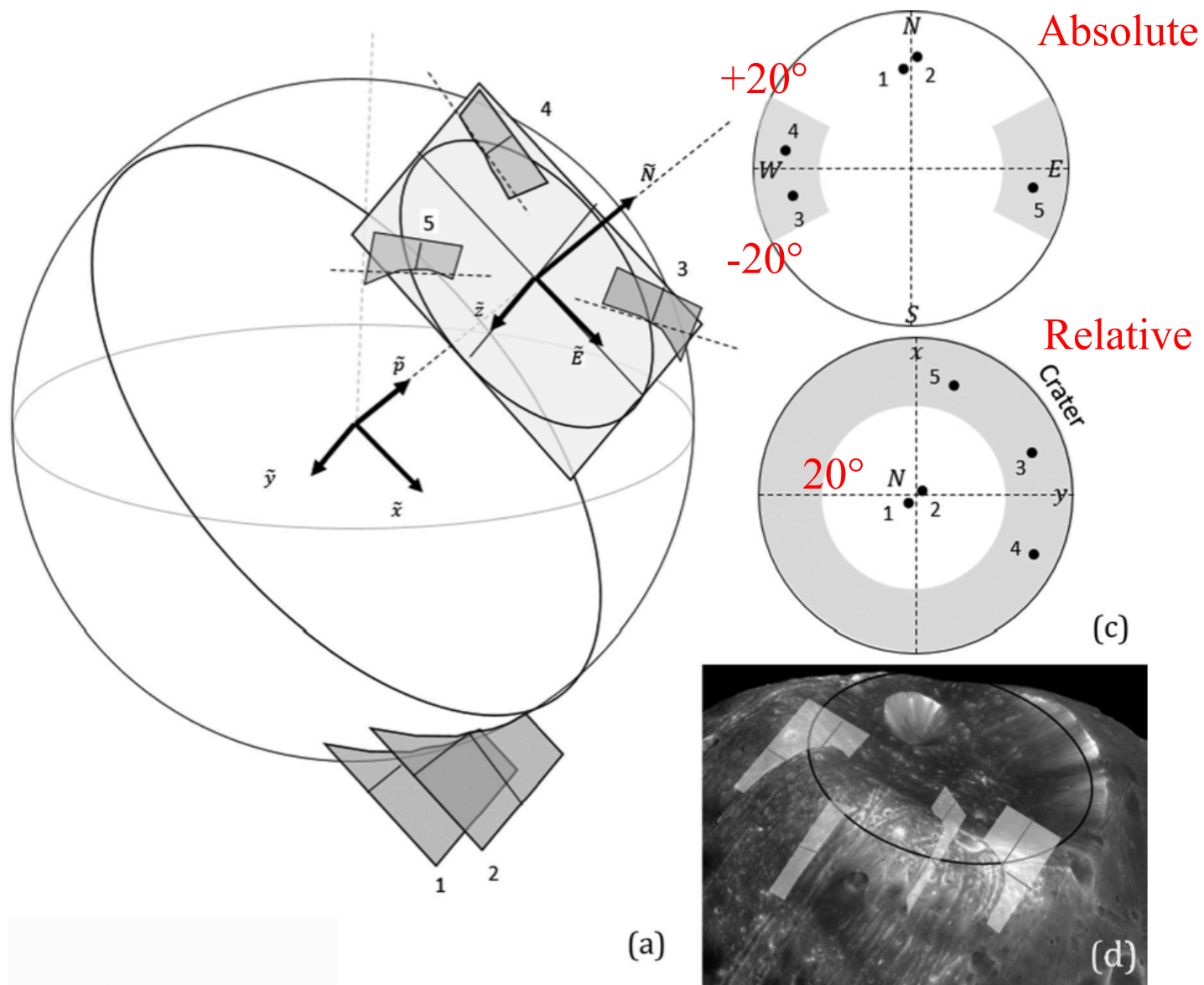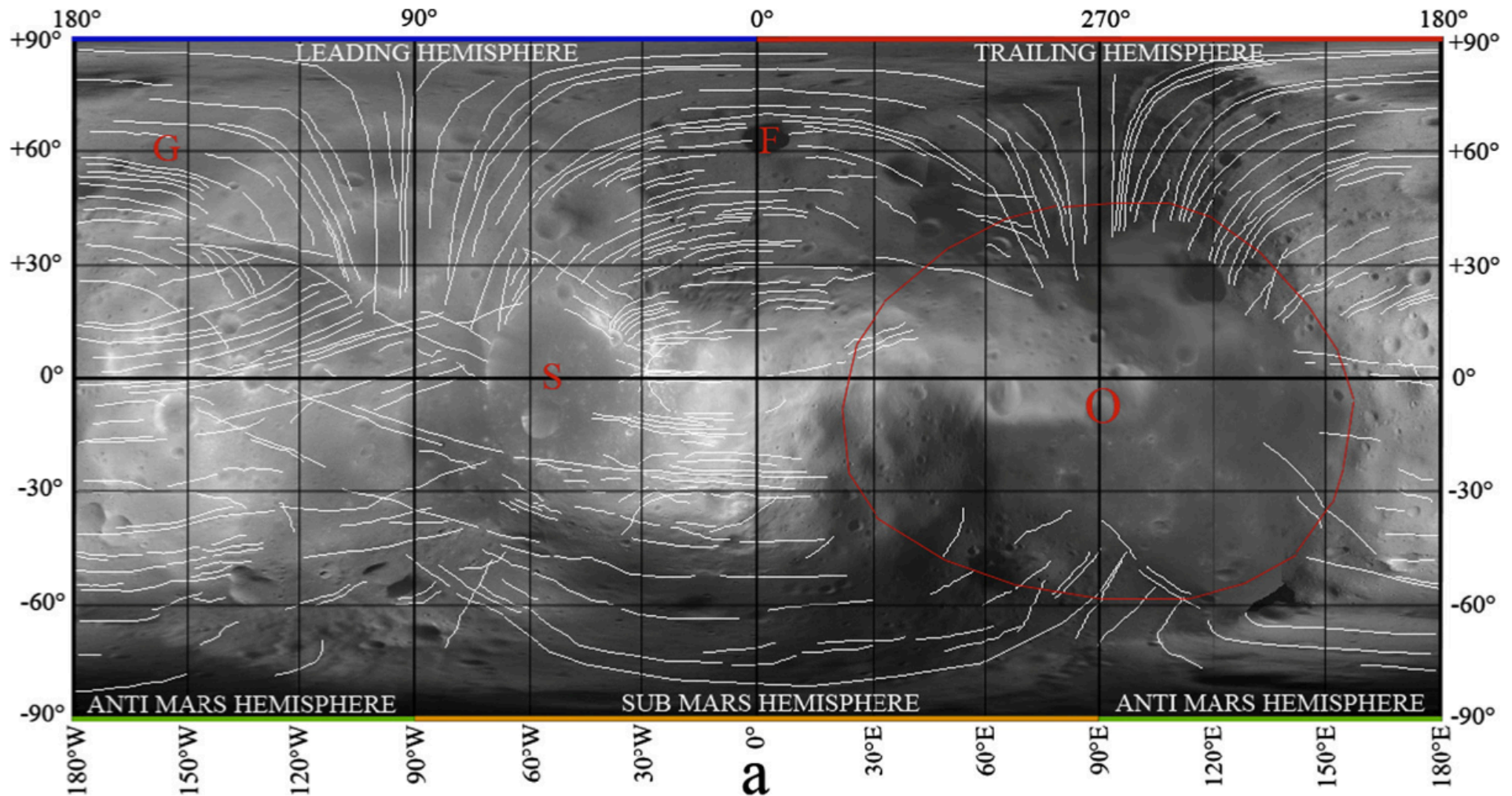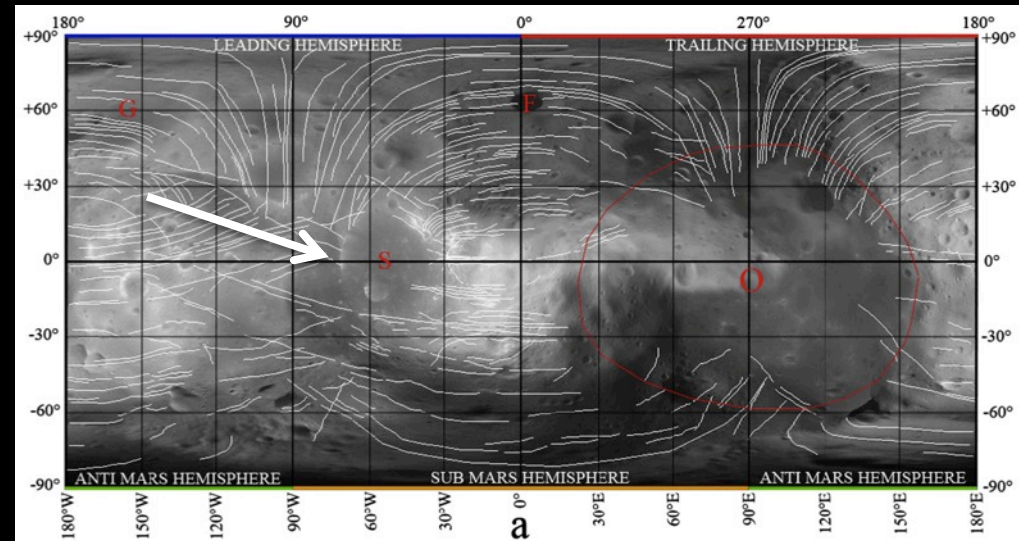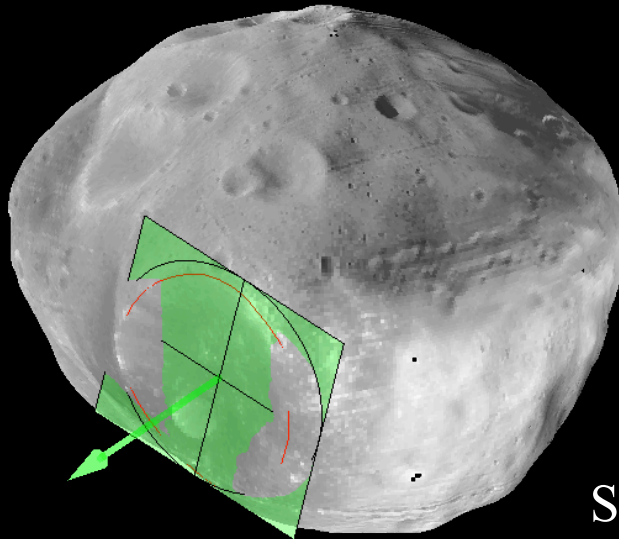

Fig. 1. Definition of the plane π_i, semi-circumference c_i and the plane vector P_i projected according to the top view in (a). In (b) are the dip-angle α and dip-direction δ of the plane with respect to the horizontal one.

But what kind of reference system?

Absolute

+20°

-20°

Relative

20°

Crater

(a)

(c)

(d)
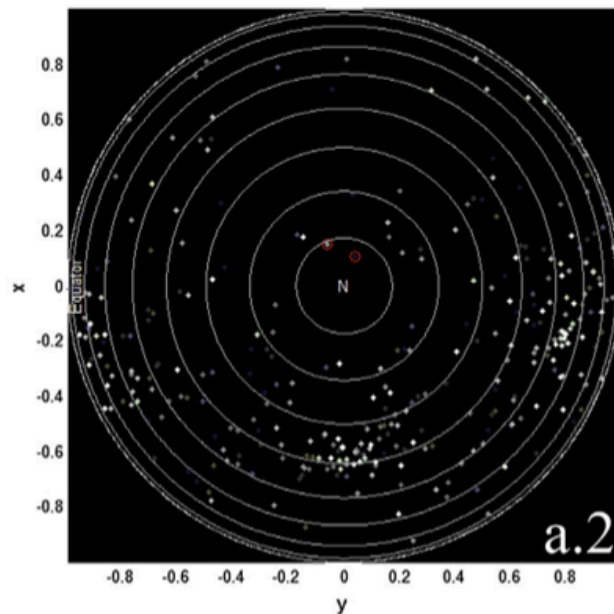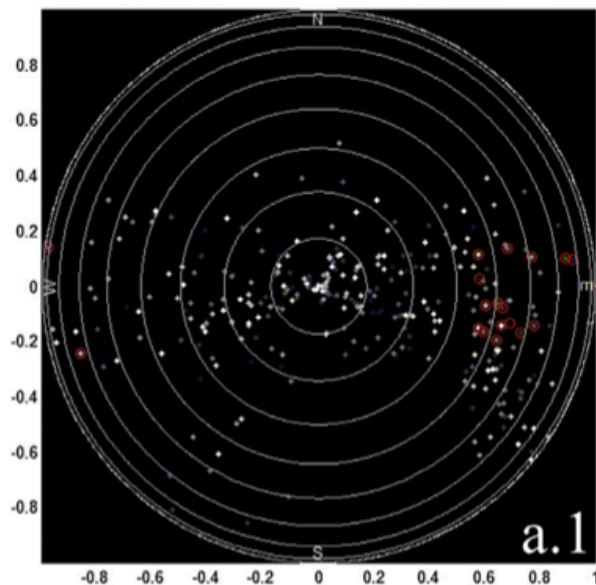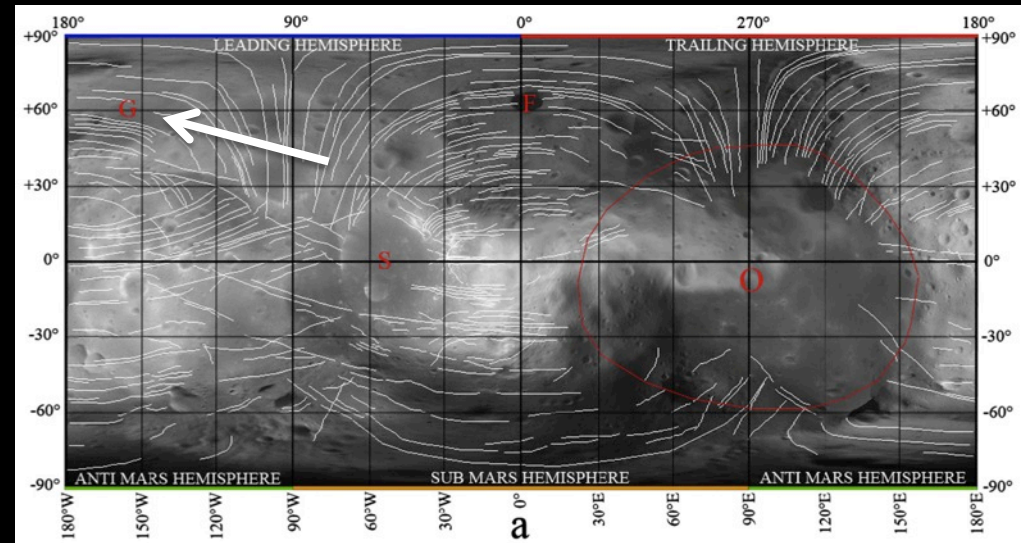
We identified 352 grooves on the Phobos surface

Stickney crater

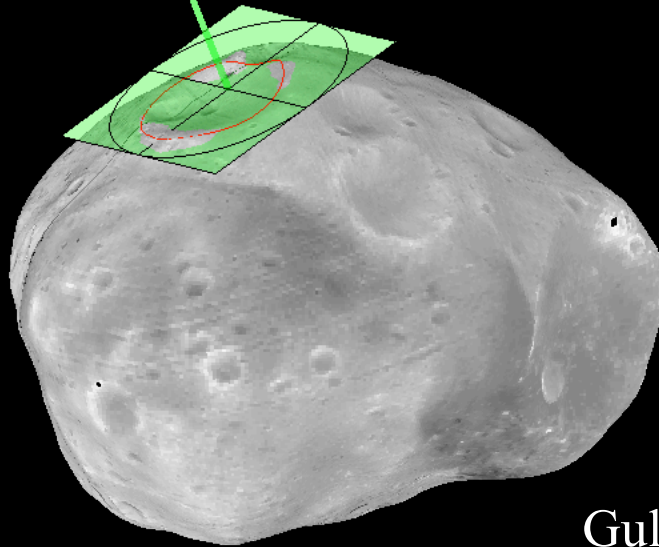Stickney crater => 5.1% Radial; 0.6% Parallel
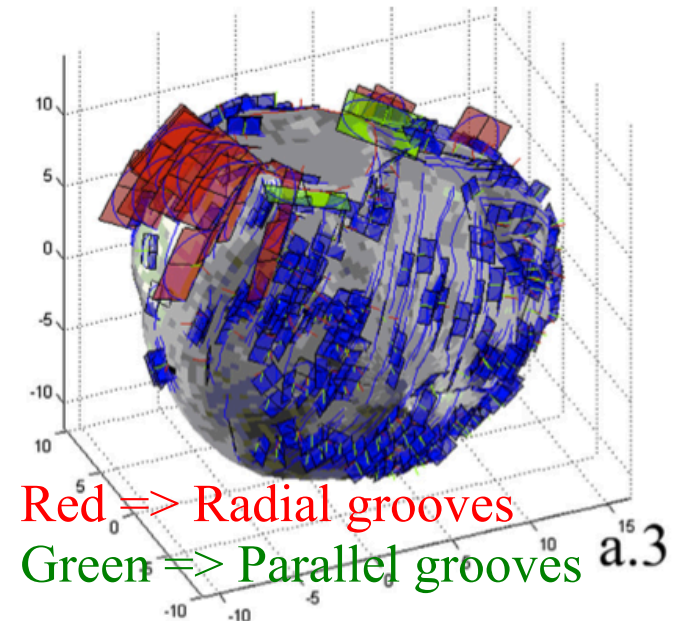
Red => Radial grooves
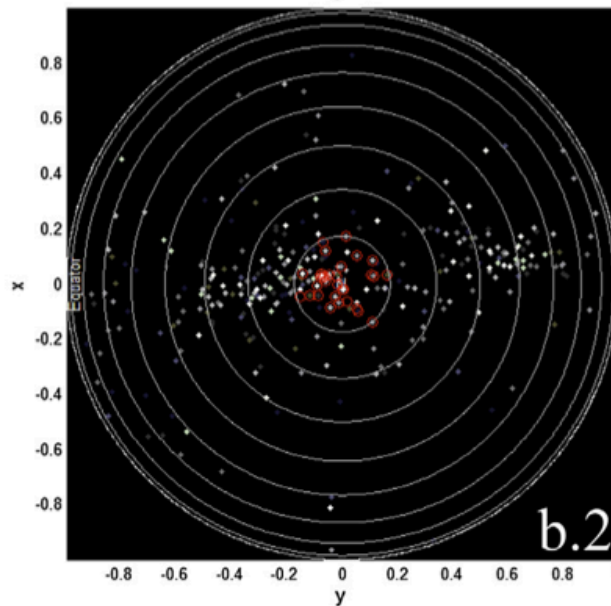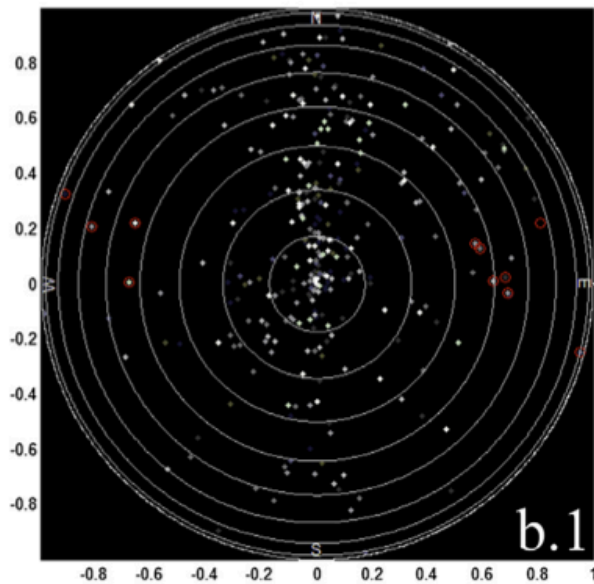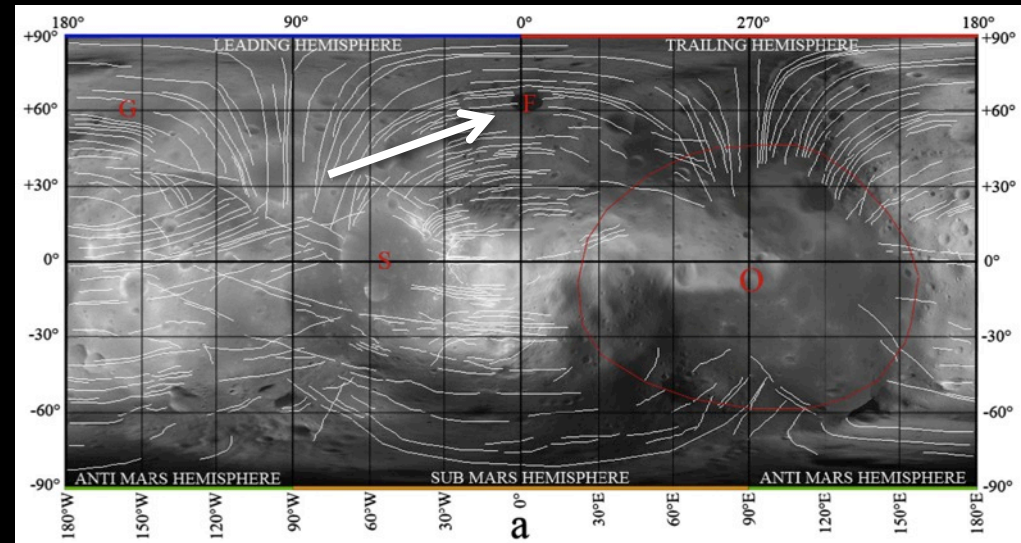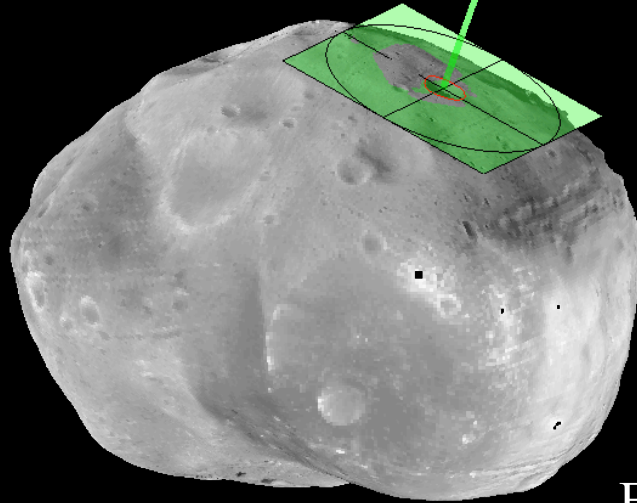Green => Parallel grooves

Gulliver crater

Gulliver crater => 3.1% Radial; 9.4% Parallel
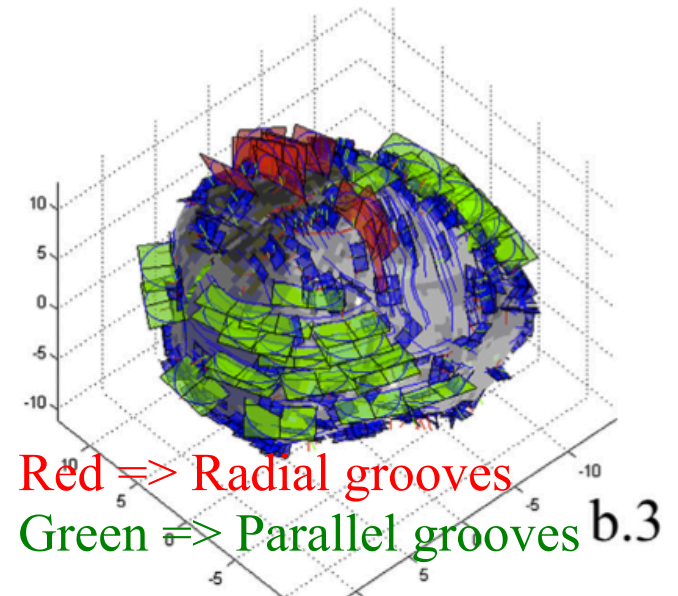
Red => Radial grooves
Green => Parallel grooves

Flimnap crater

Flimnap crater => 1.7% Radial; 7.7% Parallel

c.1

c.2

Red => Radial grooves
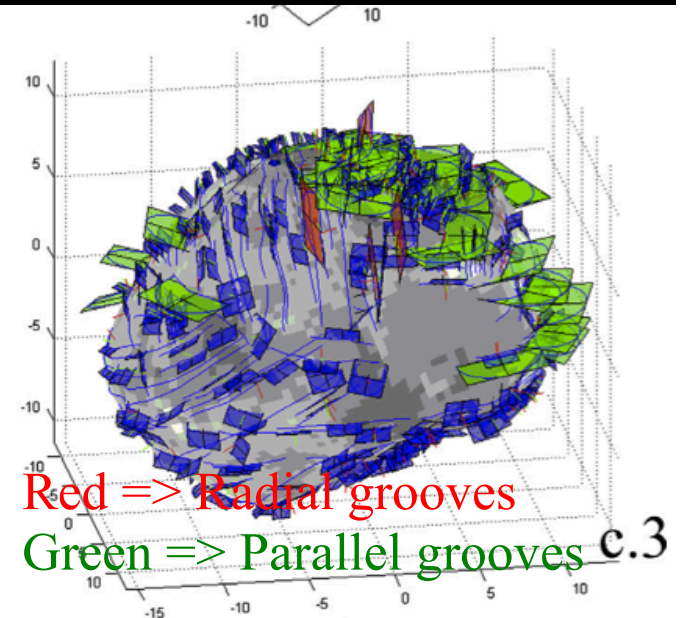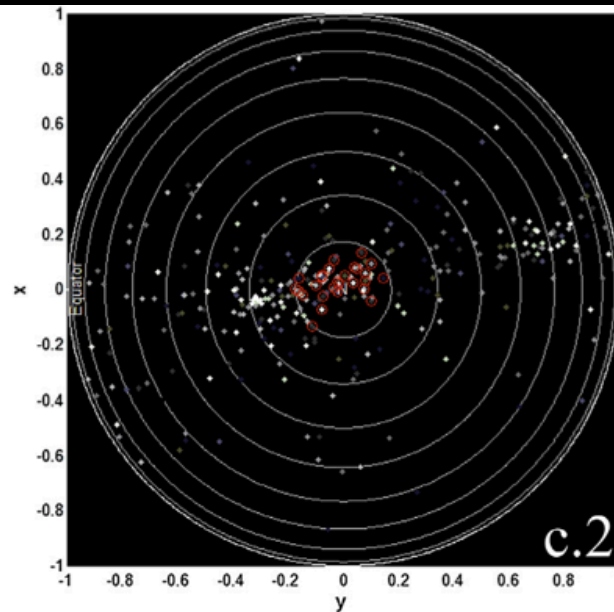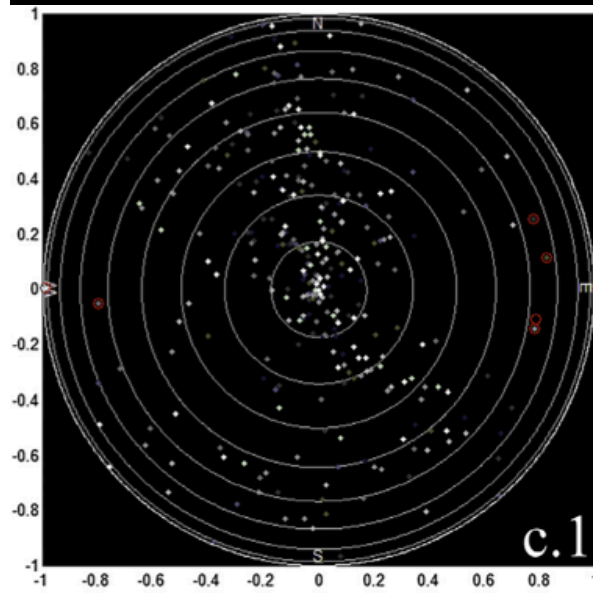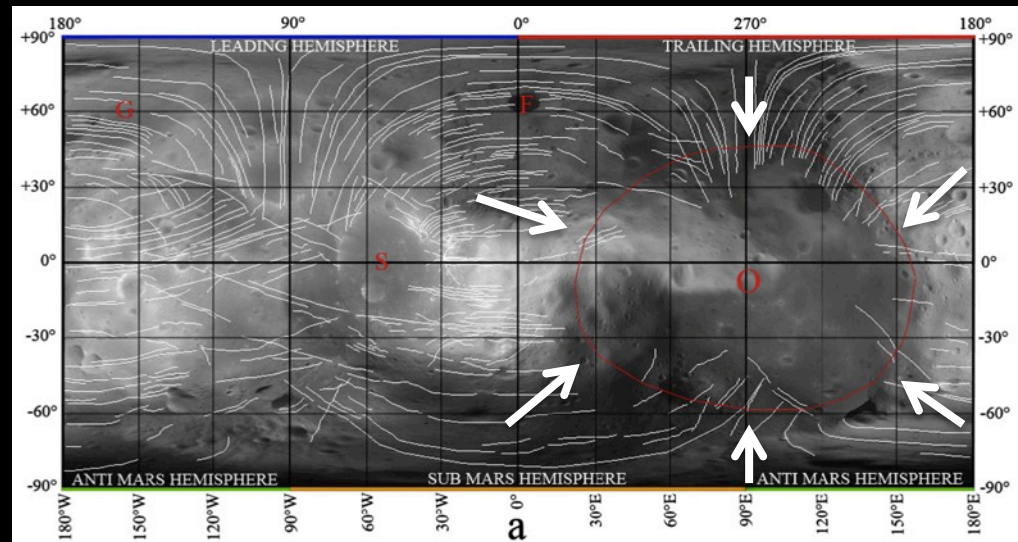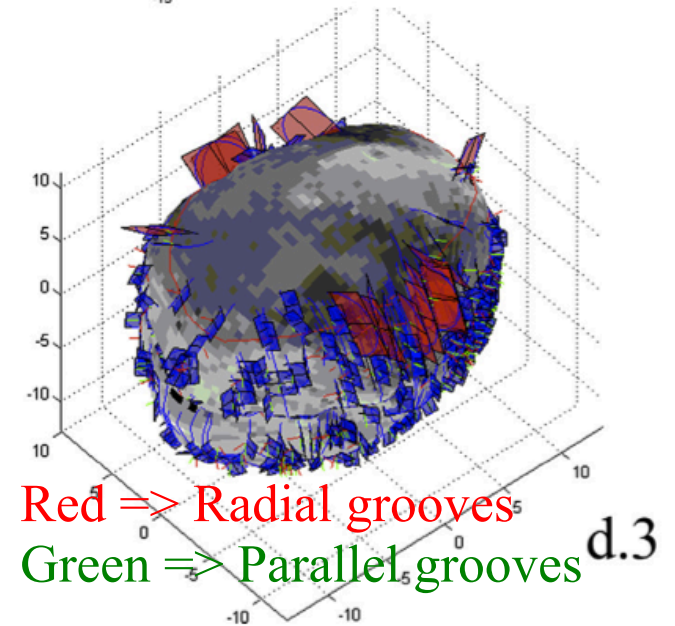Green => Parallel grooves c.3
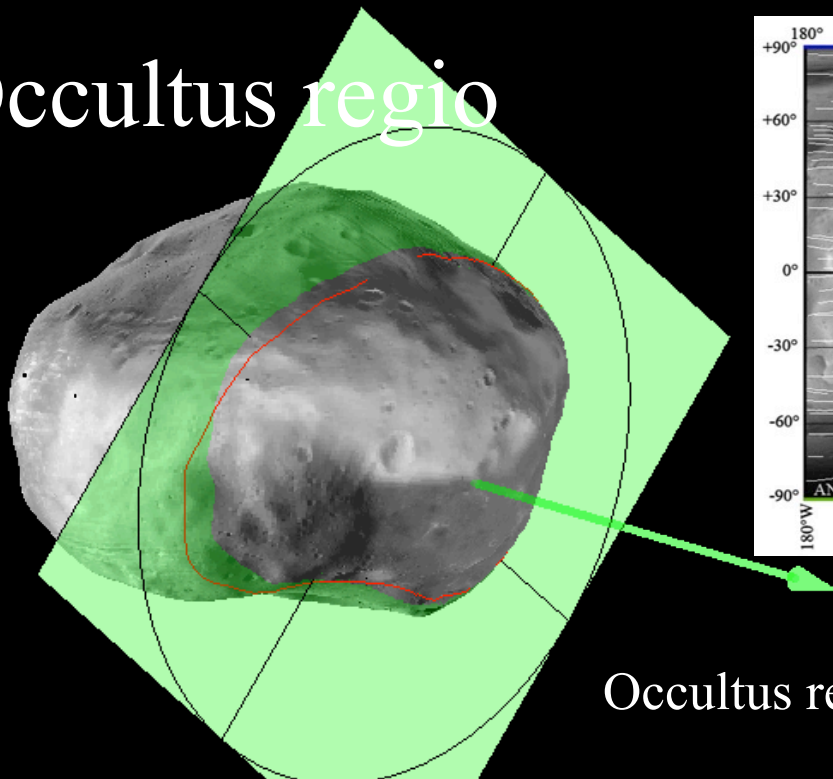
Occultus regio

Occultus regio => 6.5% Radial; 0.0% Parallel
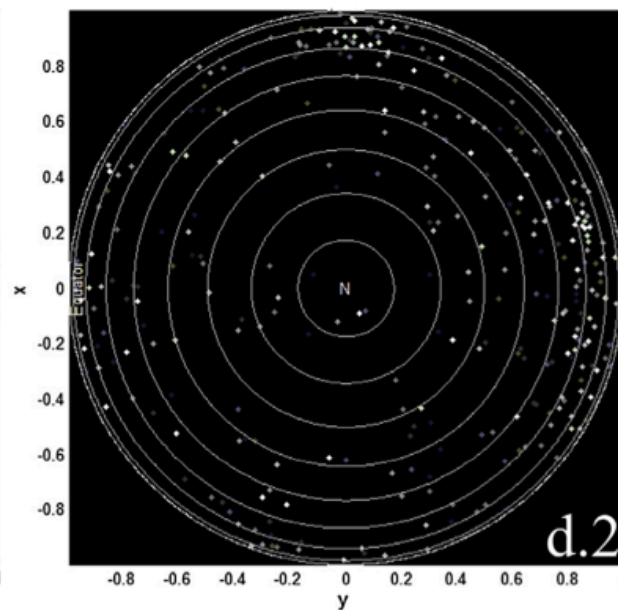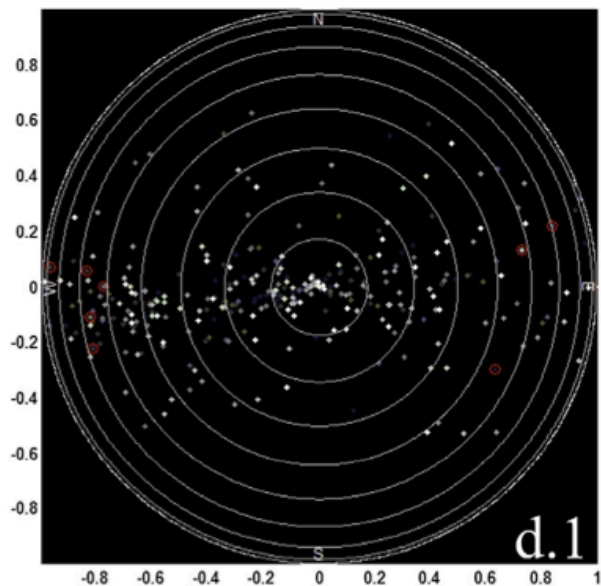
Red => Radial grooves
Green => Parallel grooves

Table 1

For all the craters analysed percentiles and numbers of plane of radial and parallel plane respect the global number of features (352).

	Stickney	Gulliver	Flimnap	Occultus
Radial	5.1% (18)	3.1% (11)	1.7% (6)	6.5% (23)
Parallel	0.6% (2)	9.4% (33)	7.7% (27)	0% (0)
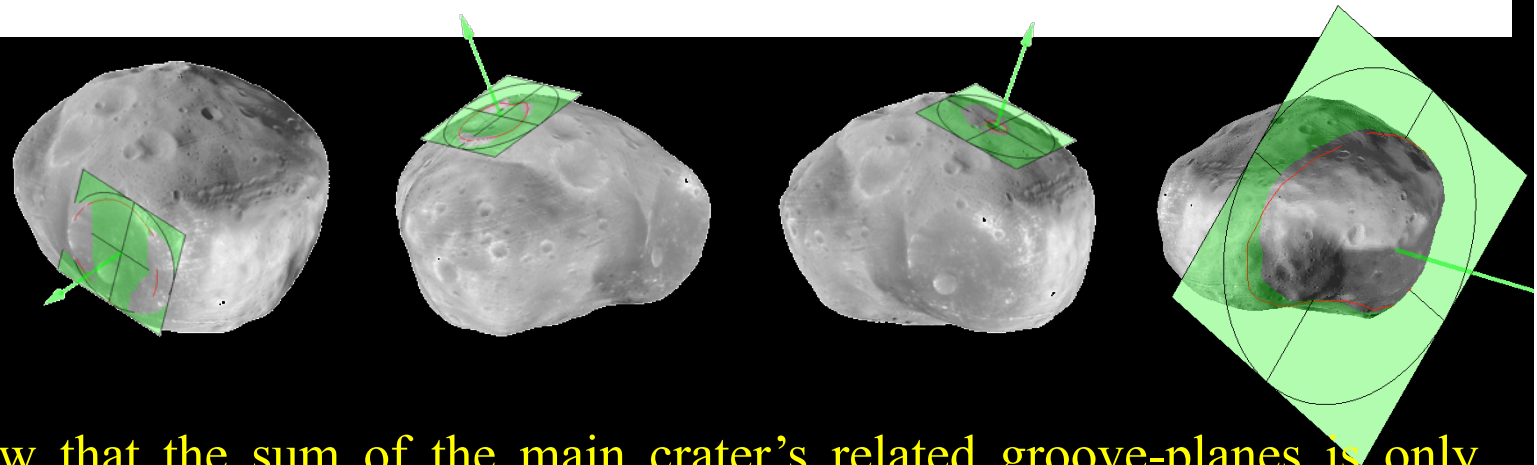
Our results show that the sum of the main crater's related groove-planes is only 27.6% with respect to the total amount (9.9% being radial). Keeping in mind that other formation scenarios, such as the grooves being chains of secondary impacts resulting from primary impact events on Mars, or the grooves as the result of Mars tidal stress, cannot explain alone the observed grooves distribution, we should start to consider a different origin for most of grooves on Phobos.

Buczkowski et al. (2008) mapped surface lineaments on 433 Eros searching for a relationship between surface morphology and interior structure. They demonstrated that some of the Eros lineaments relate to specific impact craters, while others present no obvious relationship to impact craters, proposing that 433 Eros body could derive as a fractured shard from an ancient parent body. Following the Buczkowski et al. (2008) work, we suggest that Phobos could also be a shard-like remnant of an ancient parent body. Indeed, most of the Phobos grooves are consistent with being the inherited signature of major impacts or tectonic events on a former larger parent body.
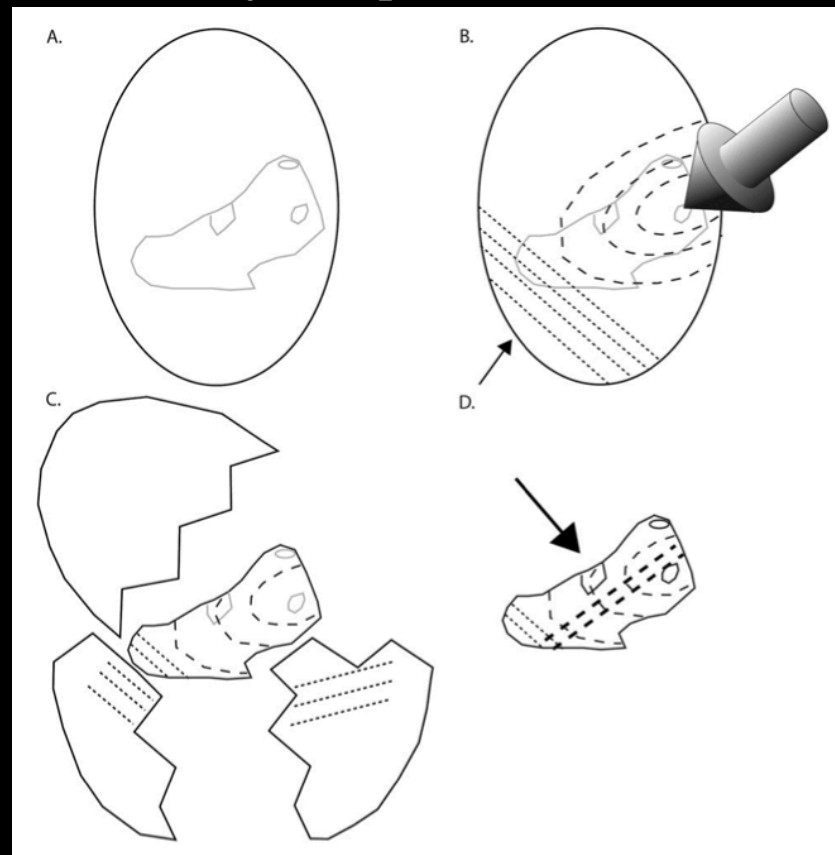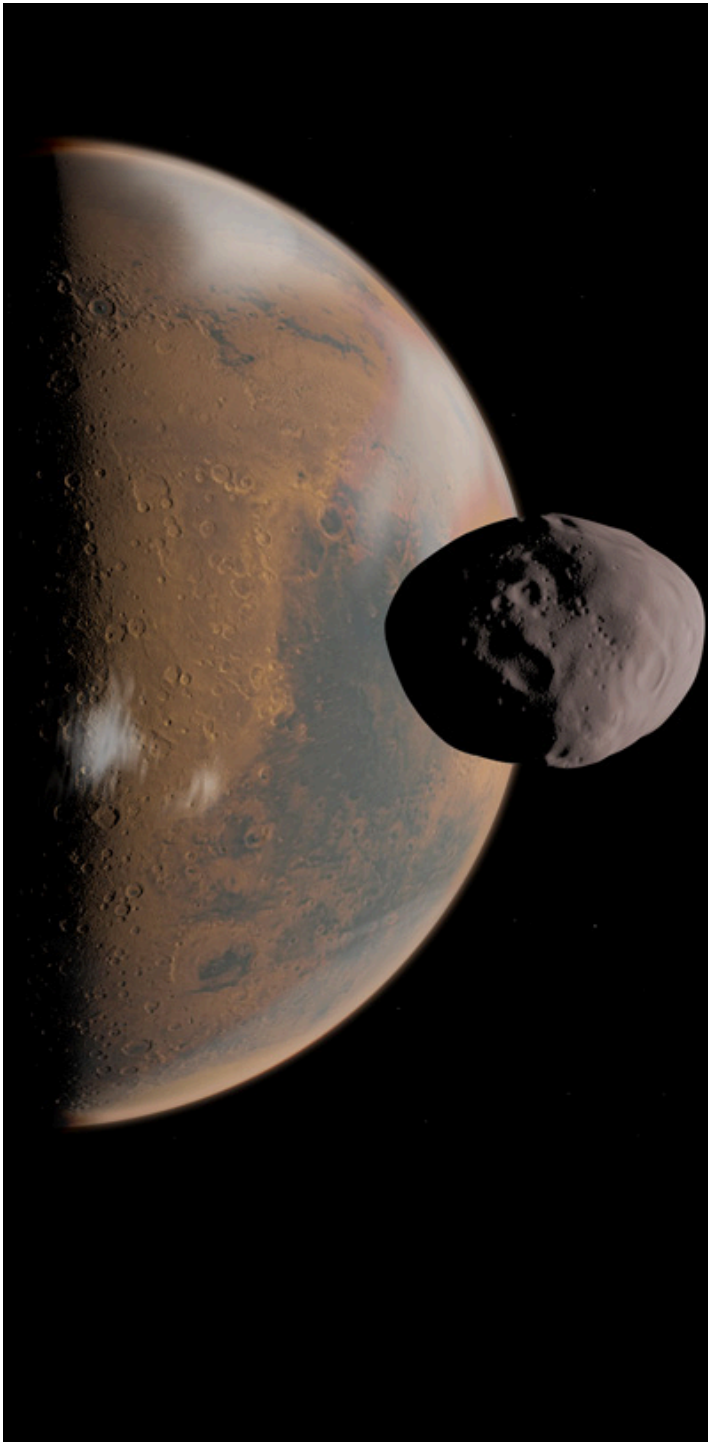
We underline that our analysis does not hint in favour of an asteroidal or an in situ origin of Phobos. Nevertheless, the possibility that a globally fractured shard could survive the tidal and drag forces during capture, can be explained by the fact that fractures are normally weakness planes which delimits portions of undeformed rock mass, and hence Phobos, could be itself a remnant of a stronger portion of the parent body because pertaining to a less deformed original block. Moreover, since Phobos is orbiting 6000 km above the martian surface, i.e. inside the Mars–Phobos Roche limit, being not torn apart by tidal forces, and displays a major crater (Stickney) at its surface without having been affected by any disruption, it should have a considerable internal strength, difficult to be justified by a rubble pile structure.

Phobos grooves and impact craters: A stereographic analysis

CrossMark

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ARTICLE INFO

ABSTRACT

Phobos parallel grooves were first observed on Viking images 38 years ago and since then they have been greatly debated leading to several formation hypotheses. Nevertheless, none of them have been favoured and widely accepted. In this work, we provide a different approach, assuming that Phobos grooves can be the expression of fracture planes, and deriving their spatial distribution and orientation on 3D reconstructions, we point out that any origin related only to craters at Phobos surface should be ruled out, since the majority of the grooves is unrelated to any craters now present at its surface. This raises the intriguing possibility that such grooves, if expression of fracture planes, are remnant features of an ancient parent body from which Phobos could have originated. Such scenario has never been considered for Phobos, though this origin was already proposed for the formation of 433 Eros grooves (Buczkowski, D.L., Barnouin-Jha, O.S., Prockter, L.M. [2008]. Icarus 193, 39). If this idea holds true, the observed groove distribution could be explained as the result of possible major impacts on the larger parent body, which were inherited by the "Phobos shard".

1. Introduction

Despite 43 years of spacecraft observations (Duxbury et al., 2014), the origin of Phobos is still unproven and a matter of great debate within the scientific community. Two main scenarios have been presented in the last decades: the so called *in situ* formation and the asteroidal capture origin. Both approaches present pros and cons that do not uniquely demonstrate this heavily debated moon's birth.

Multiple flybys of Mars Express support low bulk density of Phobos with a derived value of 1.876 ± 0.02 g/cm^3 (Witasse et al., 2014). This suggests Phobos formed either from a disk of debris (Peale, 2007), as a remnant of the formation of Mars (Safronov et al., 1986) or as the result of a collision between Mars and a large body (Craddock, 1994, 2011; Singer, 2007): the *in situ* formation scenario. Such a low density suggests that the moon might formed from re-accreted material in a rubble pile structure with a high interior porosity.

An alternate explanation for the low density of Phobos invokes water ice as part of its composition (Fanale and Salvail, 1989, 1990). Although no evidence of water ice spectral features have yet been observed on Phobos surface (Rosenblatt, 2011; Fraeman et al., 2014; Murchie et al., 2014), some content of deeper water ice cannot be a priori excluded. Another viable solution, as presented by Rosenblatt (2011) allows for both a mixture of macroporosity and water ice content. However, the corresponding error bar of the C20 gravity coefficient of Phobos measured from the close Mars Express flyby in March 2010, at a distance of 77 km, is still consistent with both a homogeneous, as well as, a heterogeneous mass distribution for the internal structure of Phobos (Witasse et al., 2014; Pätzold et al., 2014).

On the other hand, the 0.3–4.0 µm surface spectra taken from multiple areas of Phobos in more than four decades (Duxbury et al., 2014), show physical characteristics similar to low-albedo asteroids such as C-type (Masursky et al., 1972; Pang et al., 1980) or D-type (Murchie, 1999; Rivkin et al., 2002; Lynch et al., 2007; Fraeman et al., 2012, 2014; Pajola et al., 2012, 2013). These data argue against a martian-material *in situ* formation, suggesting an asteroidal capture scenario. The asteroidal capture scenario hypothesis was initially expressed by Hunten (1979) with the introduction of an aerodynamic drag due to a nebula surrounding Mars shortly after it formed. This would have required a thicker-than-expected atmosphere not justified by planetary formation processes (Burns, 1986). Since then, two other theories have been proposed to explain the capture scenario: the binary asteroid dissociation (Landis, 2009) and the collisional capture in the martian orbital region (Pajola et al., 2012). A main belt/outer main belt

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[1] These authors equally contributed to this work.

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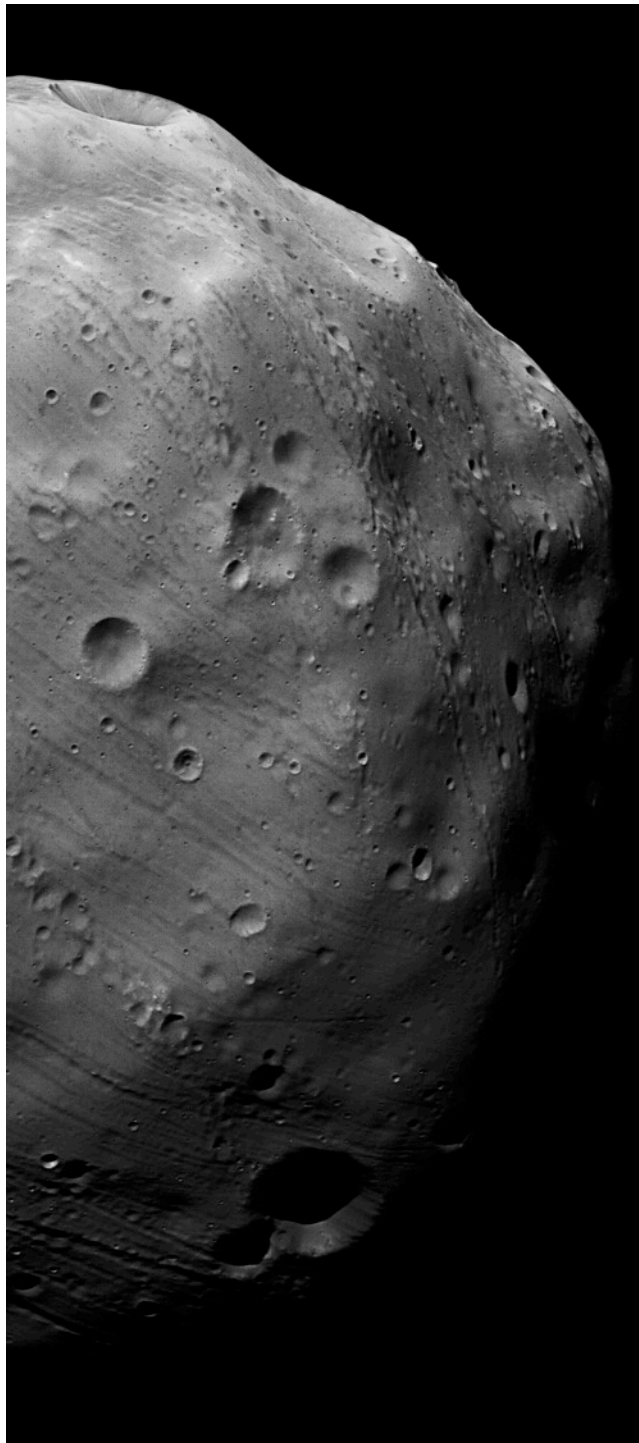
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